Unified RANS-LES model for the simulation of neutrally stratified flows

C. Peralta[1], M. Stoellinger[2], S. Heinz[2], J. Schmidt[1] and B. Stoevesandt[1]

[1] Fraunhofer IWES, Oldenburg, Germany
[2] University of Wyoming, Laramie, WY 82071

Second Symposium on OpenFOAM in Wind Energy, Boulder, 19-21 May 2014

Motivation

Fraunhofer IWES

- Site assessment for wind energy projects in complex terrain. Developed set of OF-based tools for ABL modelling: structured mesher, forest cells selector, rotor refining tool, etc.
- Mainly (u)RANS modelling with 2-equation k-epsilon model in many different flavours (EKM, AM05, Parente modifications, etc)
- Use CFD RANS simulations for wind farm optimization: flapFoam.
- All very much RANS-based. Test hybrid modelling to overcome limitations of RANS models avoiding computationally expensive (and more challenging) LES in complex terrain.
- Cooperation with University of Wyoming (S. Heinz and M. Stoellinger).

Outline

- Unified model for RANS-LES coupling.
- Case studies:
  - Homogeneous isotropic turbulent decay.
  - Actuator disk turbulent wake.
  - 3D Hill.
  - CEDVAL A1-1 cubic obstacle.
- Conclusions

Hybrid RANS-LES modelling

Fraunhofer IWES

- Many different ways to couple RANS and LES methods: interfaced (DES), segregated, etc.

Heinz et al approach [1,2]

- Hybrid RANS-LES model supported by proven theory (first principles derivation) and realizable.
- Scale information only via timescale model: involve same velocity model.
- Time scale model describes continuous variations between RANS and LES scale: simulation without discontinuities near interfaces.

[1] Heinz S Theor. Comp. Fluid Dyn. 21, 99–118 (2007)

[2] Heinz S Monte Carlo Methods Appl. 14 311–329 (2008)

Unified RANS-LES model

Fraunhofer IWES

- Hybrid RANS-LES developed from model for the evolution of turbulent velocities PDFs, implied from underlying stochastic turbulent model.
- Hierarchy of deterministic models (LUM, NLUM, etc). Same structure of RANS and LES equations.
- Select time scale from $\tau_L = \min(\tau_{LES}, \tau_{RANS})$.[3]

This presentation: rough wall unified model for atmospheric flows.

[3] Gopalan H, Heinz S and Stoellinger M K J. Comp. Phys 249 (2013)

Unified RANS-LES model

Fraunhofer IWES

- Quadratic stress tensor model.
- The modelled stress tensor is given by [4]

$$\tau_{ij}^{d} = -2\nu_t \widetilde{S}_{ij} - \frac{3\nu_t^2}{k}\left[\widetilde{S}_{ik}\widetilde{\Omega}_{kj} + \widetilde{S}_{jk}\widetilde{\Omega}_{ki} - 2\widetilde{S}_{ik}\widetilde{S}_{kj}^{d} + \frac{2}{3}\widetilde{S}_{nk}\widetilde{S}_{kn}\delta_{ij}\right]$$

- with the modelled turbulent viscosity ν_t given by

$$\nu_t = C_k\, k\, \tau_L$$

- with $\tau_L = Tr\, L/\sqrt{k},\ Tr = min(\Delta/L, 1),\ L = k^{1.5}/\epsilon$.
- $Tr = 1$ (pure RANS), $Tr < 1$ (LES).
- $\Delta = \max(\Delta x, \Delta y, \Delta z)$.

[4] Stoellinger M K, Gopalan H, Kazemi E K and Heinz S AIAA Journal 2013-0747 (2013)

$k - \epsilon$ RANS-LES model

- Using the $k - \epsilon$ model for ABL flows, the integral length scale is based on the turbulent dissipation rate ϵ: $L = k^{1.5}/\epsilon$.
- Evolution equation for the turbulent kinetic energy

$$\frac{Dk}{Dt} = \frac{\partial k}{\partial x_k}\left[(\nu + \nu_t)\frac{\partial k}{\partial x_k}\right] + P_k - \frac{k}{\tau_L}$$

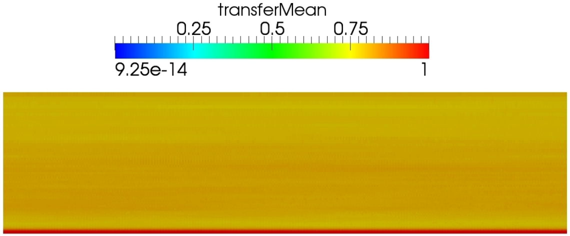
- Evolution equation for ϵ

$$\frac{D\epsilon}{Dt} = C_1\frac{\epsilon}{k}P_k - C_2\frac{\epsilon^2}{k} + \frac{\partial}{\partial x_k}\left[\left(\nu + \frac{\nu_t}{\sigma_\epsilon}\right)\frac{\partial \epsilon}{\partial x_k}\right]$$

- with model constants $C_\mu = 0.09$, $C_1 = 1.44$, $C_2 = 1.92$, $\sigma_\epsilon = 1.3$.

transfer function

- Can set $\tau_L = L/\sqrt{k}$ to enforce pure RANS mode.
- Typically hybrid grids such that $\Delta \ll L$ near surface (see below).



Wall function for smooth/rough surfaces

Fraunhofer IWES

- Follow Parente et al wall function formulation.[5]
- Overcome limitations of standard wall functions: base wall fns on aerodynamic roughness z_0.
- Fix u_w and ϵ_w at 1st cell center z_p, as in Richards and Hoxey 93.[6]
- Calculate P_k at $z + z_0$: avoid peak of TKE at the wall.
- Law of the wall for smooth and rough walls $u = (u_*/\kappa)\ln(E'z^{+\prime})$

$$E', z^{+\prime} = \begin{cases} E, \ \frac{z_p u_*}{\nu} & \text{smooth} \\ \frac{\nu}{z_0 u_*}, \ \frac{(z_p + z_0) u_*}{\nu} & \text{rough} \end{cases}$$

[5] Parente A, Gorlé C, van Beeck J and Benocci C Boun.-Lay. Met. 140 411–428 (2011)

[6] Richards P J and Hoxey R P J. Wind Eng. Ind. Aerod. 46 145–153 (1993)

Implementation in OpenFOAM

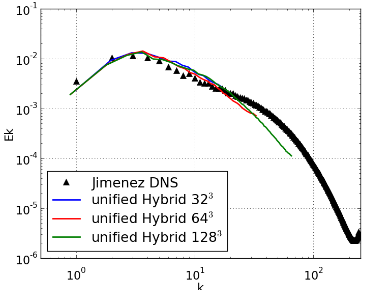
Fraunhofer IWES

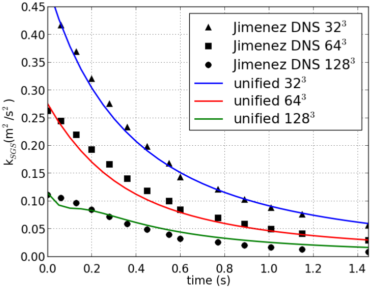
- Libraries and solver implemented in OpenFOAM 2.1.1.
- Second-order central difference scheme for convection terms in momentum equation.
- PISO algorithm for pressure-velocity coupling.
- PBiCG method for all variables except pressure.
- Algebraic multigrid solver for pressure.
- Time marching using a second-order Crank-Nicolson scheme.
- Can turn-off nonlinear stress term, use in pure RANS mode, soft/rough wall.

Test cases

DNS comparison

- Comparison with DNS of decaying homegenous isotropic turbulence in periodic cubic domain (Jimenez et al [7]).
- Unified model compares very well for even the coarsest meshes.

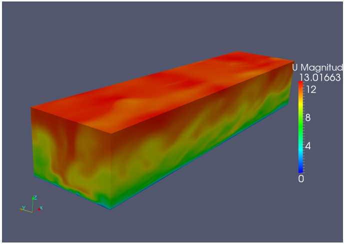




[7] http://torroja.dmt.upm.es/turbdata/agard/, with thanks to Samuel Chang for help with the data

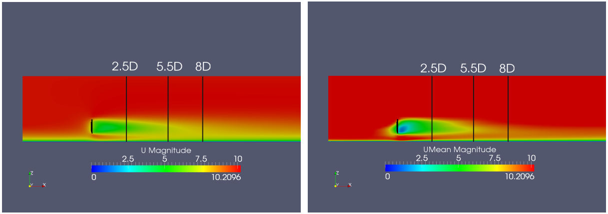
Wind turbine wake modelling

- Sexbierum experiment (1992): 300 kW, 30 m diameter turbine, single wake. [8]
- Turbine modelled as uniformly loaded actuator disk ($F = 0.5\rho A C_t U_\infty^2$).
- Performed cyclic precursor (SOWFA style).

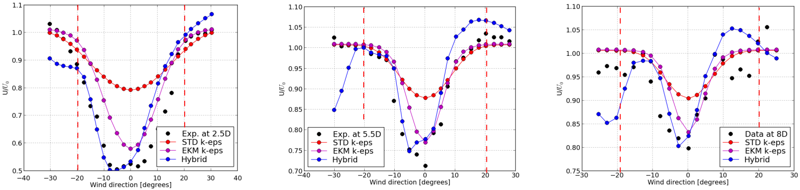


[8] Cleijne JW. Results of Sexbierum wind farm. Report MT-TNO Apeldoorn. 92–388 (1992)

- Wake comparison (EKM=El Kasmi and Masson $k-\epsilon$).[9]



- Wind speed deficit

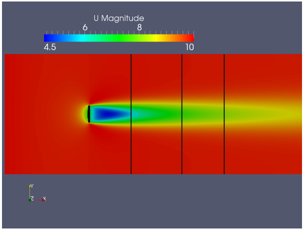


[9] El Kasmi A and Masson C. J. Wind Eng. Ind. Aerodyn. 96, 103-122, (2008)

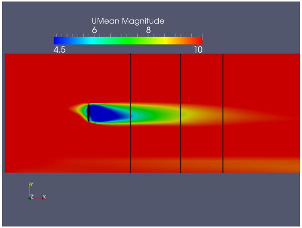
Deviations from the data

- Cut at z=35, wake comparison and transfer function effect. Lines at 2.5D, 5.5D and 8D.
- Need finer mesh, proper mesh study.

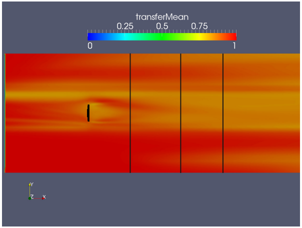
EKM



Hybrid



transfer function



3D axisymmetric hill

Fraunhofer IWES

- Wind tunnel measurements from University of Tokyo.[10]
- Axisymmetric hill ($r_{max} = 0.42$ m base radius, $h_{max} = 0.2$) with height defined by

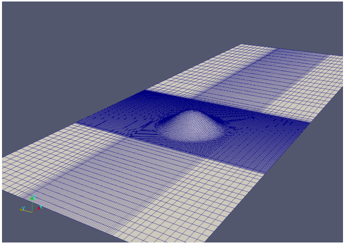
$$h(r) = \begin{cases} h_{max}\, 0.5\ [1 + \cos(2\pi r / r_{max})] & \text{if} r < r_{max} \\ 0 & \text{otherwise} \end{cases}$$

- Hill model positioned 2 m downstream of inlet test section of wind tunnel ($6 \times 2.2 \times 1.8$ m^{-3}).

[10] Takahashi T, S Kato S, Murakami S, R Ooka M, Fassy Y M and Kono R J. Wind Eng. Ind. Aerodyn. 93 155–169 (2005)

3D axisymmetric hill

- Computational domain containing entire test section.

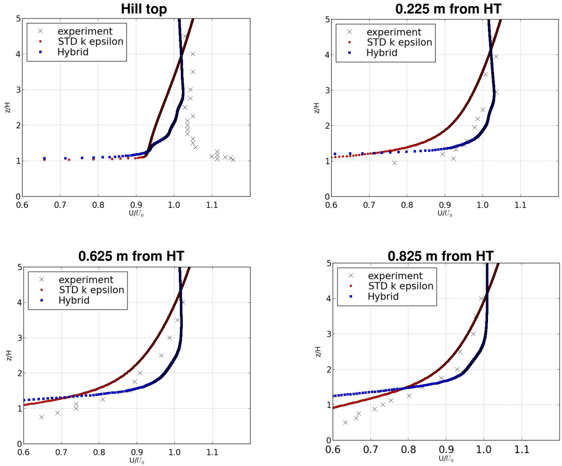


- Structured mesh with `terrainBlockMesher`[11] 200 × 90 × 60 cells, 1.04 hexas, refined around hill.
- Hill and floor rough walls with $z_0 = 0.0122$ m. Smooth boundaries at ceiling and side walls.
- Interpolated experimental data (U,k) imposed at inlet.
- STD $k - \epsilon$ simulation used as precursor and comparison.

[11] https://github.com/jonasIWES/terrainBlockMesher

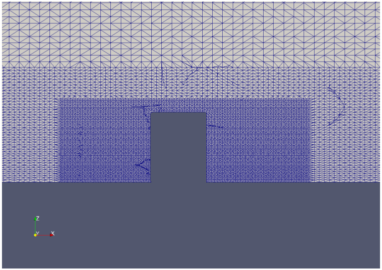
Results 3D hill

- Measurements for velocity in streamwise direction along hill top.



Cube obstacle: CEDVAL A1-1

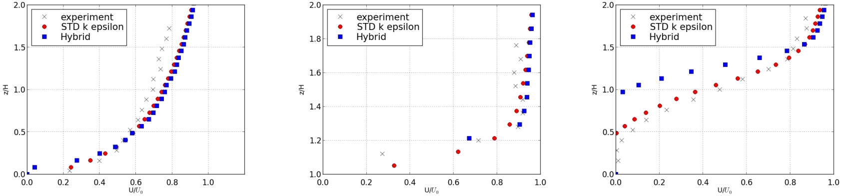
- Hamburg University wind tunnel measurements.
- Single rectangular building: 0.125 m height, z_0= 0.0007, $u_* = 0.377$ m s^{-1}.
- Unstructured mesh with `snappyHexMesh`, $5 \times 2.6 \times 1.0$ m^{-3}, 870776 cells.



CEDVAL A1-1 Results

Fraunhofer IWES

- Vertical velocity profiles before, on top and after the obstacle.



Conclusions

- Unified RANS-LES model based on the LES model of Heinz et al.
- Validated in neutral ABL in flat (rough) terrain, channel flow.
- We performed additional tests in simple geometries: single wind turbine wake, 3D hill, CEDVAL cube.
- Preliminary results promising.
- Underestimation of TKE (modelled + resolved).

Future work

Fraunhofer IWES

- Test other ways to provide turbulent inflow.
- Test in real complex terrain benchmark cases: Bolund, Alaiz (wind tunnel case).
- Unified RANS-LES model to be combined with dynamic procedure in LES region.